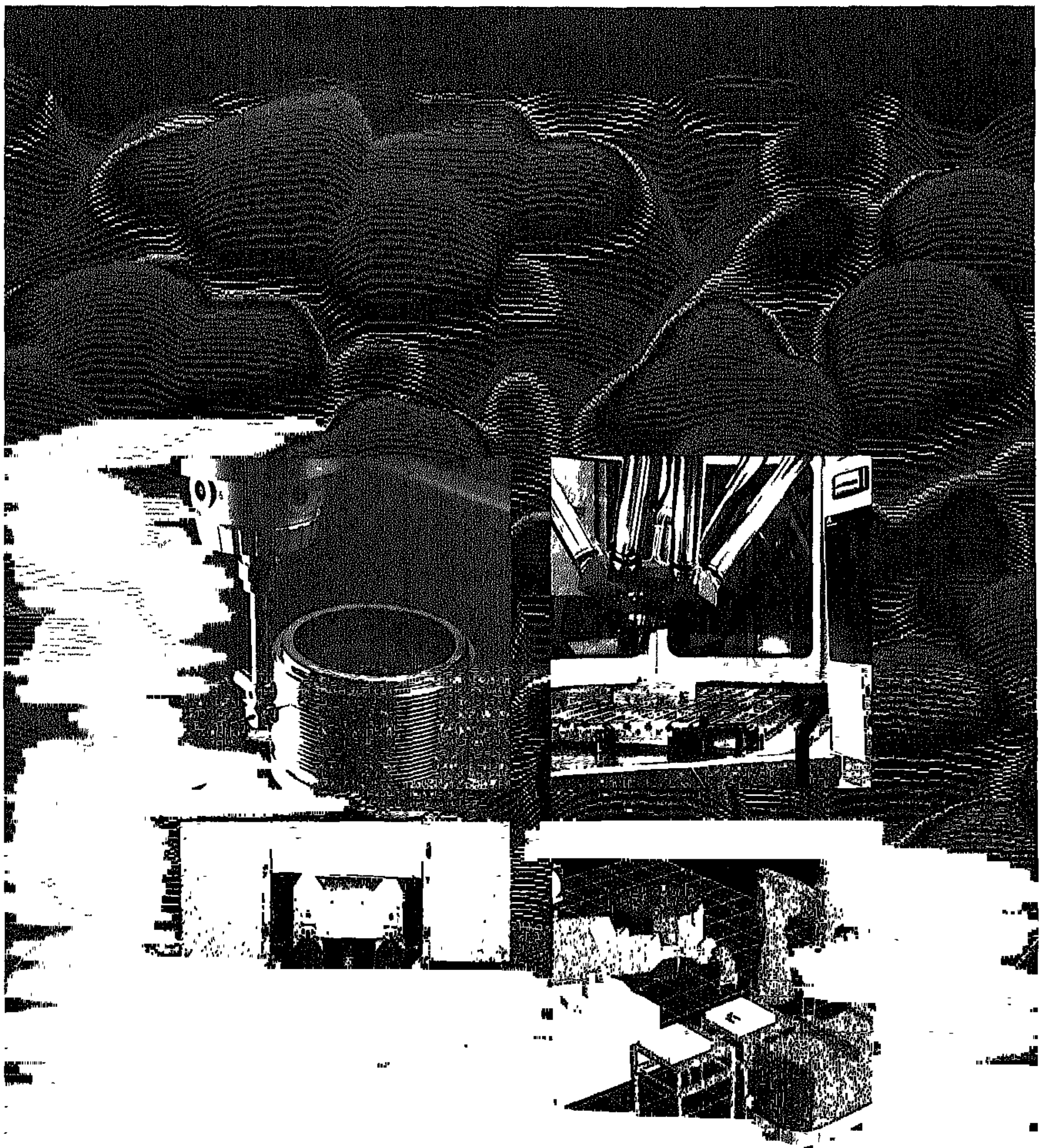
NIST MANUFACTURING ENGINEERING LABORATORY



U.S. DEPARTMENT OF COMMERCE

TECHNOLOGY ADMINISTRATION

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

The National Institute of Standards and Technology was established by Congress "to assist industry in the development of technology needed to improve product quality, to modernize manufacturing processes, to ensure product reliability and to facilitate rapid commercialization ... of products based on new scientific discoveries"

An agency of the U S Department of Commerce's Technology Administration, NIST's primary mission is to promote U S economic growth by working with industry to develop and apply technology, measurements, and standards. It carries out this mission through a portfolio of four major programs

- a competitive Advanced Technology Program providing cost-shared awards to industry to develop high-risk technologies that can enable significant commercial advances,
- a grassroots Manufacturing Extension Partnership helping small and medium-sized companies to adopt new technologies;
- a strong laboratory effort planned and implemented in cooperation with industry and focused on infrastructural technologies such as measurements, standards, evaluated data, and test methods, and
- a far-reaching quality outreach program associated with the Malcolm Baldrige National Quality Award.

BUDGET
$1 billion
(FY 1995 estimated operating resources from all sources)

STAFF
About 3,200 scientists, engineers, technicians, and support personnel, plus some 1,200 visiting researchers each year

SITES
Gaithersburg, Md (headquarters 234-hectare campus) and Boulder, Colo (84-hectare campus)

MAIN RESEARCH AREAS IN NIST LABORATORIES
Electronics and electrical engineering
Manufacturing engineering
Chemical science and technology
Physics
Materials science and engineering
Building and fire research
Computer systems
Computing and applied mathematics

On the Cover:

Background: Atomic-force microscope image of the surface of a new type of laser-activated storage disk being developed by an industrial collaborator. Images of the material's atomic topography (purple represents the highest point, followed by green, yellow, and red) support efforts to improve the firm's manufacturing process.

Top Left: A coordinate measuring machine probe records coordinates along screw threads to measure pitch diameter. An array of MEL projects addresses issues related to CMM performance and application to help companies improve their inspection and quality assurance procedures.

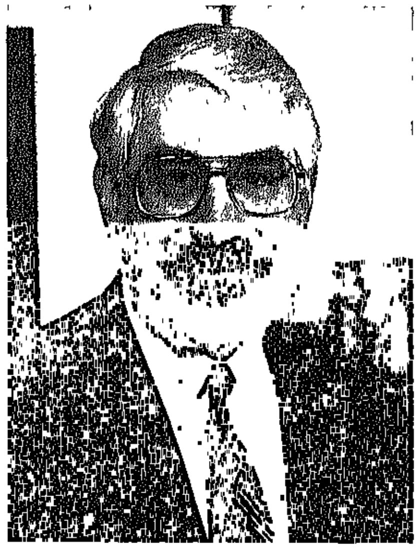
Top Right: Candidate for a universal machine tool, an octahedral-hexapod machine will be the target of research in MEL's new Advanced Machine Tool Structures Testbed.

Bottom Left: This U.S.-made high-precision piston turning machine is used by the nation's auto makers. The manufacturer of the machine tool plans to incorporate accuracy-enhancing software developed at MEL.

Bottom Right: Computer model of a factory represents one element of a new MEL effort to develop a framework, common interfaces, and other standards necessary for creating an integrated set of computer-aided tools for planning and designing factories and production processes.

BUILDING A MANUFACTURING ADVANTAGE

In recent years, manufacturers have begun to concentrate on what they do best—their core competencies—and to look outside their companies for strong partners with complementary, value-adding strengths needed to accomplish manufacturing and business objectives As a result, manufacturers are building extensive sets of linkages—to customers and suppliers, among factories, and even between public and private research and development efforts.



At the Manufacturing Engineering Laboratory (MEL) of the National Institute of Standards and Technology, we are heading in the same strategic direction, toward building tighter, more productive relationships with our primary customers, U S manufacturers, and with other organizations pursuing complementary technology goals. NIST is explicitly charged with providing technical assistance to U S industry as it strives to improve its competitiveness MEL's part of the job is to help manufacturers develop and apply technology, measurements, and standards.

We are moving more aggressively to tackle the technical challenges embodied in opportunities created by rapidly evolving information and manufacturing technologies that are changing the rules of competition MEL intends to make a real difference in this fast-paced, high-stakes competition by working in partnership with U.S industry We aim to be an attentive, responsive partner that performs research and services that manufacturers can use to their advantage

MEL provides services basic to improving manufacturing capabilities and speeding technology development and application. We help companies overcome measurement problems, incompatibility barriers to integrated manufacturing, and other infrastructural obstacles to manufacturing improvements We do it by solving these problems generically so that the solutions are available to a broad cross-section of industry This leveraged approach eliminates wasteful duplication of effort by individual companies struggling to surmount the same technical hurdles

Technological opportunities for improving manufacturing and business processes abound for all, including competitors Each innovation and discovery raises the bar and creates moving targets that U.S manufacturers must pursue relentlessly

There are many ways—formal and informal—to work with MEL and other NIST laboratories and programs. With a simple phone call or e-mail message, you can learn more about what we have to offer

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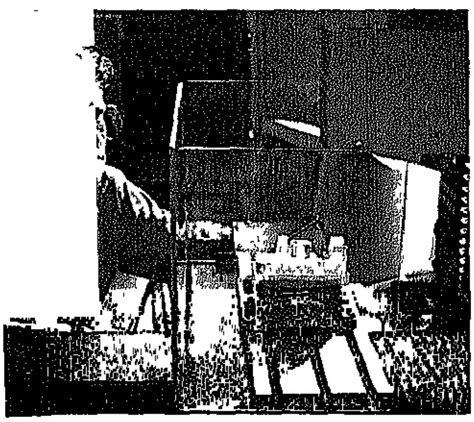
BASIC RESOURCE FOR MANUFACTURERS

TECHNOLOGY MEASUREMENTS STANDARDS

Technology-driven changes are reshaping all manufacturing industries This transformation is delivering opportunities for U S firms to increase flexibility, raise productivity, improve quality, shorten product-development cycles, and strengthen relationships with suppliers and customers

The Manufacturing Engineering Laboratory at the National Institute of Standards and Technology helps U.S industry turn technological opportunity into competitive advantage With a staff of about 300 people, MEL works with the nation's diverse manufacturing sector to develop and apply technology, measurements, and standards

From accuracy-enhancing software used in U S -made machine tools to underlying concepts embodied in the scanning tunneling microscope, scores of MEL-developed standards, measurement techniques, and technologies are already at work in factories and laboratories Building on its tradition of industrial collaboration, MEL is stepping up efforts to meet the technical needs of U.S manufacturers in areas ranging from advanced machine tool controllers to enterprise integration and from single-point diamond turning to fabricating the next generation of integrated circuits.



Prototype of an open-architecture machine controller undergoes testing. Standard, flexible interfaces will enable better performance and easier programming, while reducing development, maintenance, and training costs.

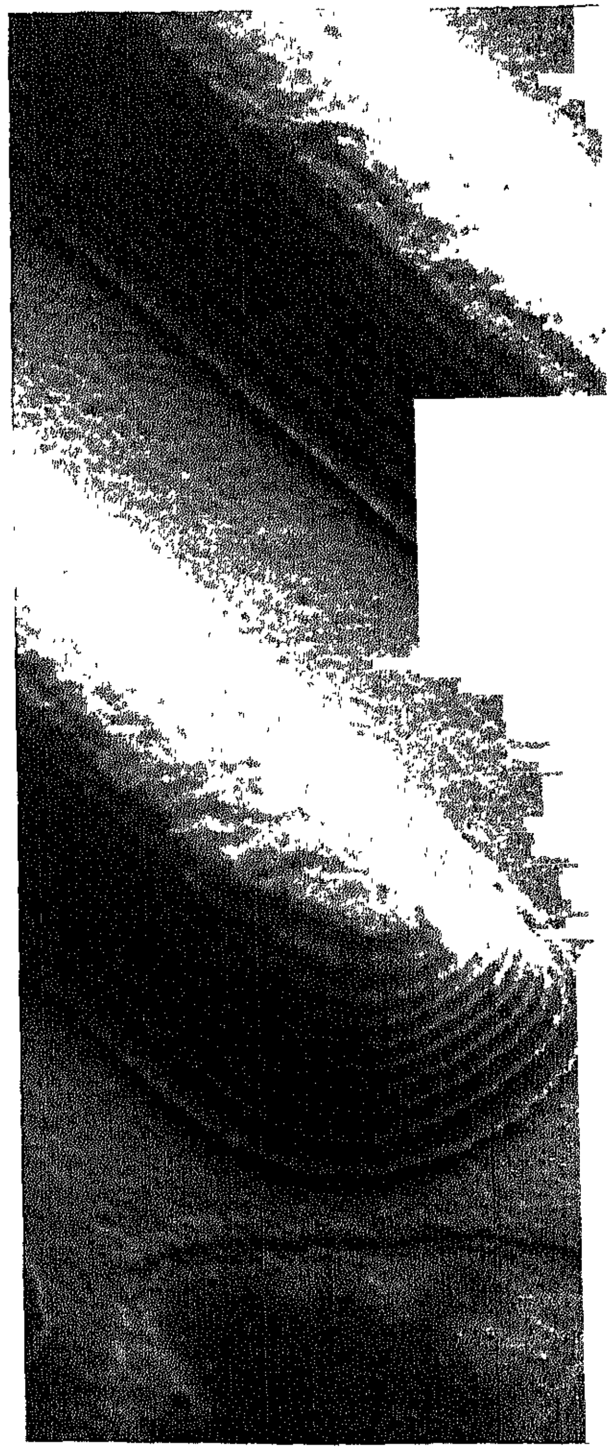
STRONG, RESPONSIVE PARTNER

U S manufacturing executives recently rated their companies' performance in applying advanced technology to products and processes as average or below average. In the crucially important matter of rapidly introducing new products, American executives graded their abilities as "D," as compared to Japanese executives who rated their capabilities as "A– "

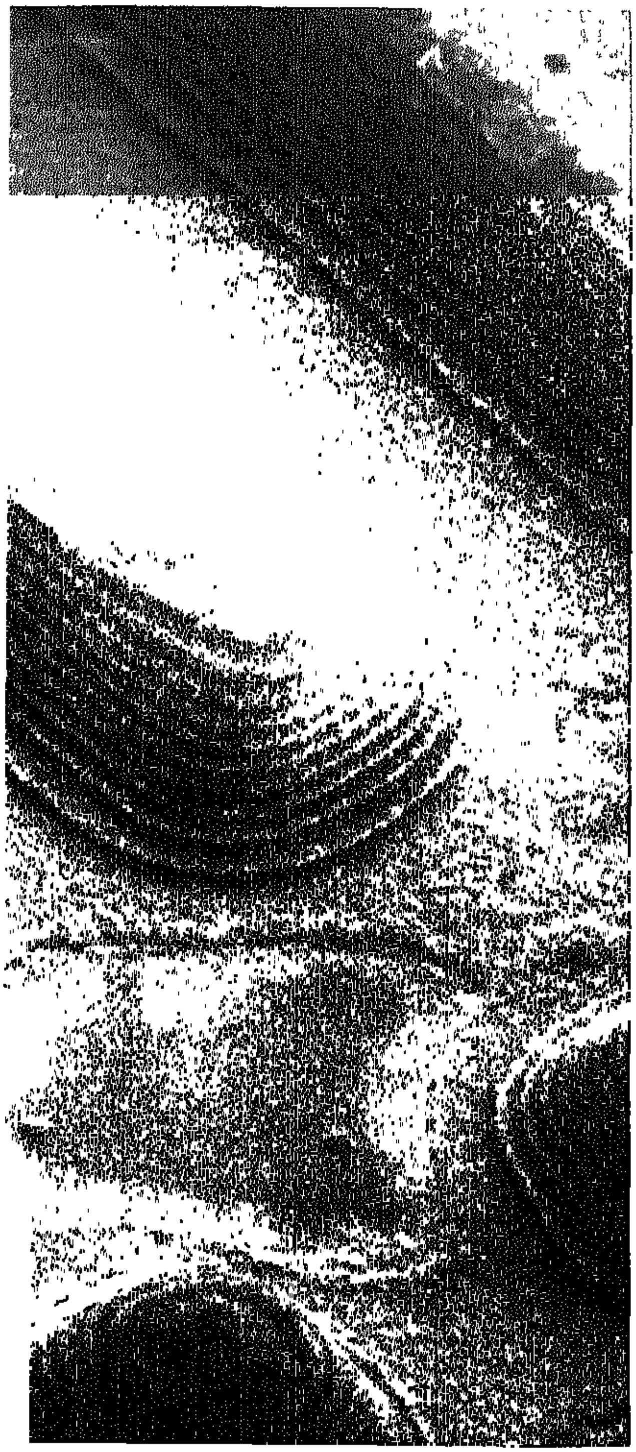
MEL represents a strategically important technical resource for U.S. manufacturers as they vie for leadership in developing and applying technology The laboratory's primary areas of expertise—measurement and information technology—are central to all aspects of manufacturing.

The connection between measurement and manufacturing is a direct one: If a company cannot measure, it cannot control processes or manufacture to specification. Nor can it meet the requirements of increasingly demanding customers Measurement accuracy sets the upper limit on product quality, on machine-tool performance, and on the optimization of processes and entire production systems Consequently, MEL's metrology research and services pave the way to improvements in industries as diverse as metalworking, aerospace, textiles, semiconductors, and automobiles.

To be a strong partner to U.S. manufacturers, the Laboratory develops measurement capabilities well beyond the state of the art in industry. In a typical year, hundreds of U.S companies call on MEL for calibrations, Standard Reference Materials, and other high-end measurement services that are not available in the private sector or, in some cases, anywhere else in the world. (Measurement services are listed on pages 18–20.)



New high-resolution image analysis system reveals differential removal of a photoresist on silicon during etching processes that create integrated-circuit patterns. The system, developed by MEL and two industrial partners, is used to analyze scanning electron microscope images.



Information and networking technologies present opportunities for increasing productivity, shaving costs, cutting time, and seizing market opportunities. MEL concentrates on enabling infrastructural technologies essential to realizing these important benefits Examples are

- interfaces and standards, such as STEP, the evolving universal product data exchange standard that enables direct, computer-to-computer communication of product information within and between companies,
- architectures for integrating machines, work cells, factories, and even groups of companies;
- data dictionaries and software tool kits for building applications of information technology that work with one another; and
- conformance tests for ensuring the compatibility of hardware and software products

Progress toward the next generation of manufacturing—hinted at by such terms as agile manufacturing and virtual enterprises—depends on these building-block technologies: Without them, companies and industries won't be able to get there from here.

COOPERATION IS OUR STYLE

MEL's goal is to produce useful results for its customers—U.S. manufacturers. To do that, the lab must work closely with industry and with all types and sizes of manufacturers. And we do. Representatives of hundreds of companies informally consult with MEL staff members and attend the Laboratory's R&D planning and priority-setting workshops. About half of MEL professional staff members participate in industry-led voluntary standards-setting committees, and one in five technical personnel are involved in cooperative R&D agreements, or CRADAs, with U S companies.

At MEL's Automated Manufacturing Research Facility (AMRF), co-sponsored by the U.S Navy, more than 50 companies and more than 40 universities have sent researchers to work on projects focused on next-generation automation technologies. Seventy-five firms donated equipment to support R&D at this national testbed In addition to increased understanding of problems in computer-integrated manufacturing—a benefit that continues to pay dividends—work at the decade-old AMRF has yielded more than 30 actual or planned commercial product or process applications adopted by more than 60 companies. This work also has contributed significantly to the development of nearly 40 current or emerging national and international standards, such as the Manufacturing Automation Protocol, the Standard for the Exchange of Product Model Data, and the Dimensional Measurement Interface Specification

HIGHER AIMS, BOLDER INITIATIVES

NIST has been assigned important roles in expanding efforts to forge productive technology partnerships between government and industry. Here are some of the ways in which MEL is responding to meet its responsibilities in manufacturing.

National Advanced Manufacturing Testbed (NAMT). The evolutionary successor to the Laboratory's successful Automated Manufacturing Research Facility, the NAMT will be a national testbed for the "virtual" factory. Here, MEL and its partners will integrate, operate, test, benchmark, and refine advanced manufacturing technologies and demonstrate approaches to distributed design, engineering, and manufacturing operations. Using the interfaces and other

PRACTICAL ASSISTANCE FOR MANUFACTURERS

Companies that work with MEL or use its measurement services represent a broad cross-section of the manufacturing sector. They range from "Fortune 500" firms, such as Caterpillar, Boeing, Timken, and IBM, to small start-up companies, such as the Optex Communications Corp., which aims to commercialize a novel, high-capacity memory technology but needs to refine its manufacturing processes.

The particulars of collaborations are equally diverse, spanning hardware and software, or the control of individual processes and the integration of entire factories. Here's a sampling of topics that MEL is addressing with industrial partners: advanced design systems; process planning; manufacturing applications of object-oriented databases, off-line programming [illegible]

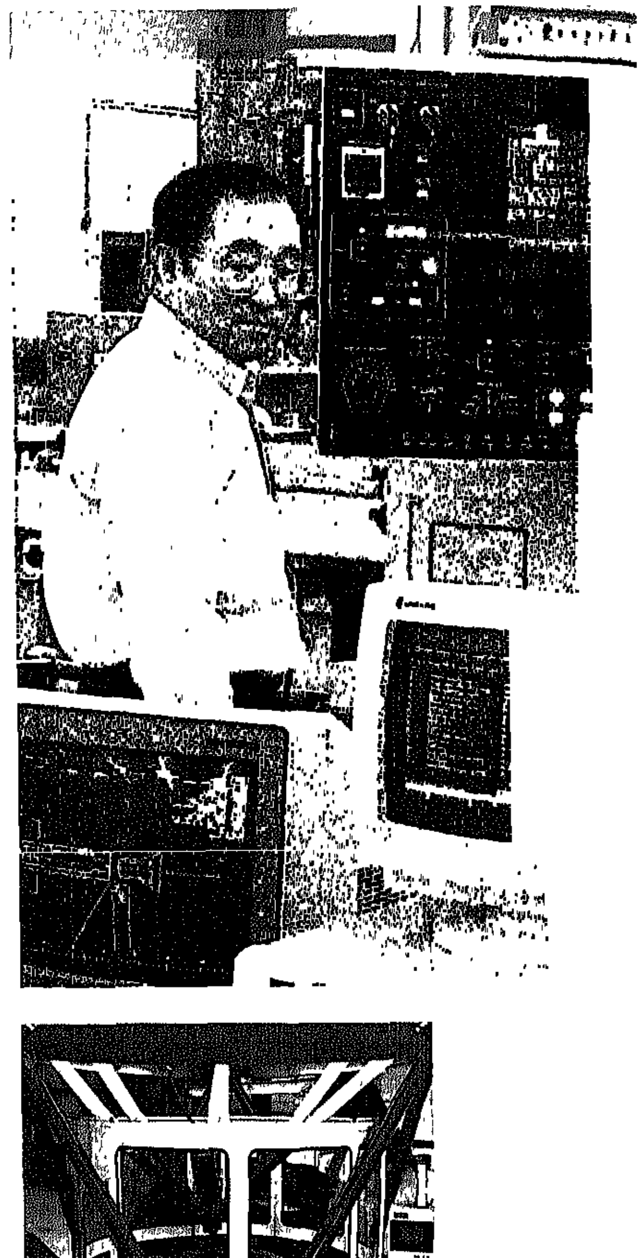
[illegible]

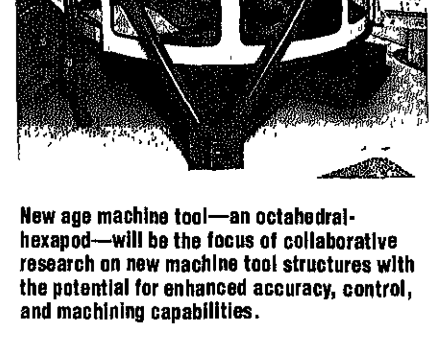
The returns, however, can be substantial, directly applicable, and, sometimes, eye opening. Consider the comments of an executive of the Johnson Gage Co., an MEL partner in a project that developed a flexible computer-integrated manufacturing workstation to make high-precision fasteners for submarines at the Portsmouth Naval Shipyard in New Hampshire.

"This workstation," he wrote, "set a new standard for productivity .. [and] gave us a look at what is readily achievable in the future. All manufacturing processes can and should be controlled during the process and not after."

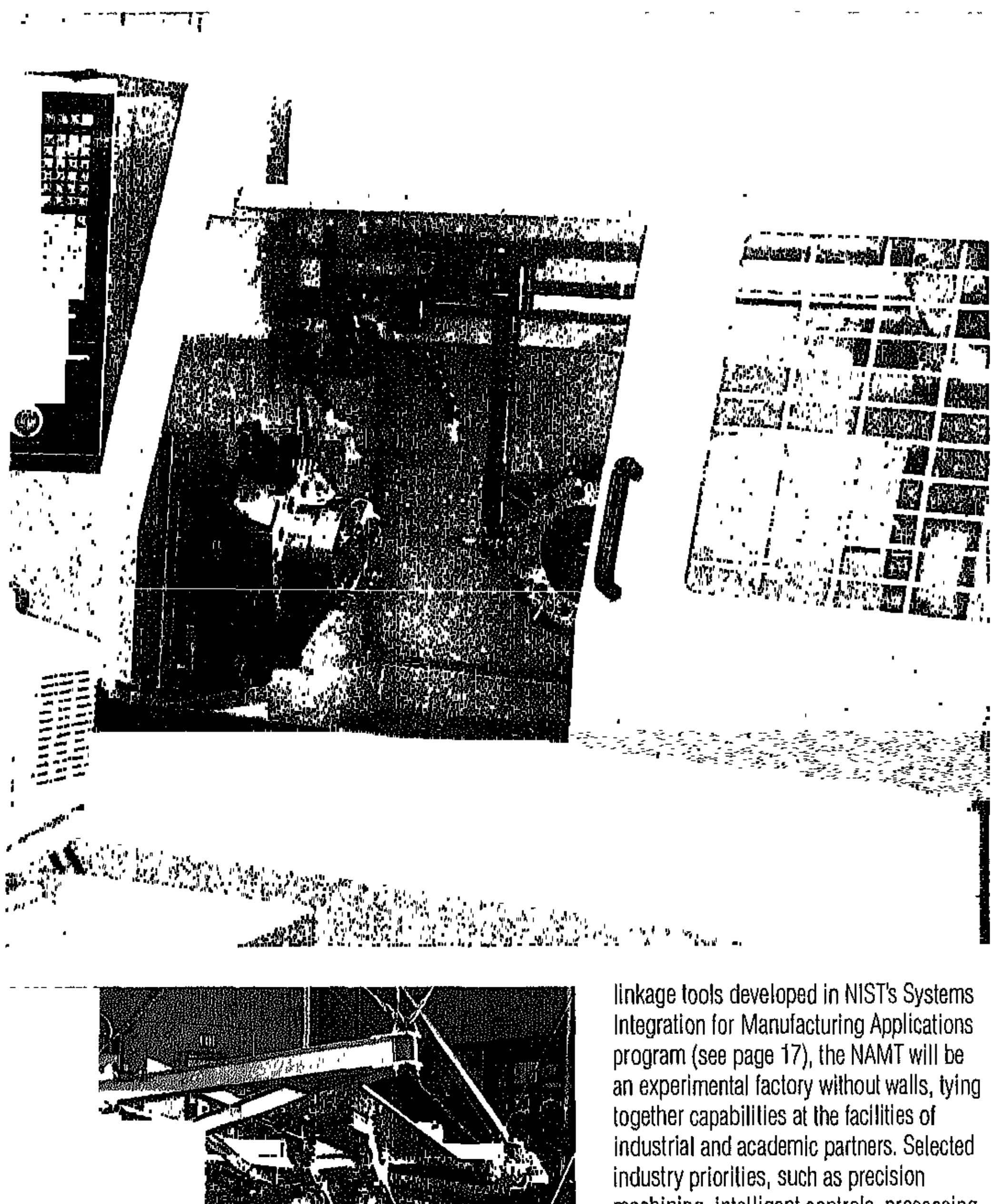
A manager at Inspection Technologies Inc. reports that another MEL-developed technology—a system for checking the accuracy of data-analysis software in [illegible]

[illegible]





New age machine tool—an octahedral-hexapod—will be the focus of collaborative research on new machine tool structures with the potential for enhanced accuracy, control, and machining capabilities.



linkage tools developed in NIST's Systems Integration for Manufacturing Applications program (see page 17), the NAMT will be an experimental factory without walls, tying together capabilities at the facilities of industrial and academic partners. Selected industry priorities, such as precision machining, intelligent controls, processing of advanced materials, engineering tools, and simulation and modeling, will be the initial focus of technical activities.

Crane for the automation age, NIST's RoboCrane can lift, precisely maneuver, and position loads in six degrees of freedom. It can be used for large-scale assembly or for manipulating tools over large working volumes.

Top: "Amazing" is how one company executive described the flexible computer-integrated workstation that MEL helped to develop for the U.S. Navy. The workstation has increased productivity by more than 300 percent and reduced the rejection rate to less than 1 percent.

Advanced Machine Tool Structures Testbed. This new testbed will study applications and control strategies for potentially revolutionary octahedral-hexapod machines and other innovative forms of machine tools Anticipated benefits of design innovations include lower costs, greater flexibility and reliability, and higher accuracy. MEL research on the experimental octahedral-hexapod will focus on developing computer-control architectures that maximize performance and versatility and on achieving submicrometer machining accuracy

Service Innovations and Leveraged Resources. To meet industry needs, MEL is moving aggressively to combine its technical resources and expertise with complementing capabilities of other federal organizations. These initiatives respond to private-sector calls for services identified as important to the competitiveness of key U.S. industries.

For example, MEL has joined with the Y-12 Plant at the Department of Energy's Oak Ridge Centers for Manufacturing Technologies and several other partners to form a national Gear Metrology Center The new center will provide services critical to improving the manufacture and quality assurance of precision gears, which account for about 30 percent of sales by the $14 billion U.S. gear industry. Services will include NIST-traceable calibrations of gear elements and master gears and special tests of first-article production gears. A representative of the American Gear Manufacturers' Association, a partner in the effort, called the center a "foundation for advanced research, testing, and development of the high-performance gearing of the future, as well as for assuring product consistency in today's highly competitive global gear market."

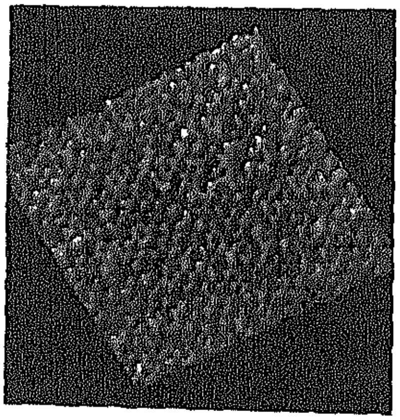
PRECISION ACCURACY QUALITY

On the quest to improve product quality and manufacturing performance, nearly all manufacturing industries are heading in the same direction—toward products with more complex shapes and features with ever smaller dimensional tolerances. The trend is most pronounced in the semiconductor manufacturing industry, which the Manufacturing Engineering Laboratory supports through several technical programs and services. These include *Standard Reference Materials for checking* the accuracy of instruments used to measure the diminishing critical dimensions of integrated circuits, research collaborations with Sematech, the consortium of U.S. chipmakers, and the Laboratory's involvement in NIST's newly begun National Semiconductor Metrology Program.

But even for manufacturers of the very large—such as aircraft, cars, engines, and agricultural equipment—tolerances have retreated into the domain of a few micrometers. Within a decade, the most demanding applications of conventional milling and turning machines are expected to require cutting accuracies approaching 1 micrometer.

MEL is racing to stay ahead of the trend toward increasing precision and accuracy. The aim is to provide industry with the measurement tools it needs, when it needs them. Pursuing that aim, the Laboratory's scientists and engineers are pushing up against nature's limits. For example, one MEL-designed instrument—the molecular measuring machine—will check the accuracy of its own measurements against the interatomic spacings and geometry of single-crystal surfaces, nature's perfect latticework.

The Laboratory's research also yields results that help companies to increase the accuracy and reliability of today's measurement systems. One recent advance will enable MEL to increase the accuracy of NIST's mass measurements by a factor of five or more. Another—dubbed the Advanced Automated Master Angle Calibration System—yielded a hundredfold improvement in the accuracy of angle measurements, which are



critical to reducing rotational errors in the manufacture of advanced optical equipment.

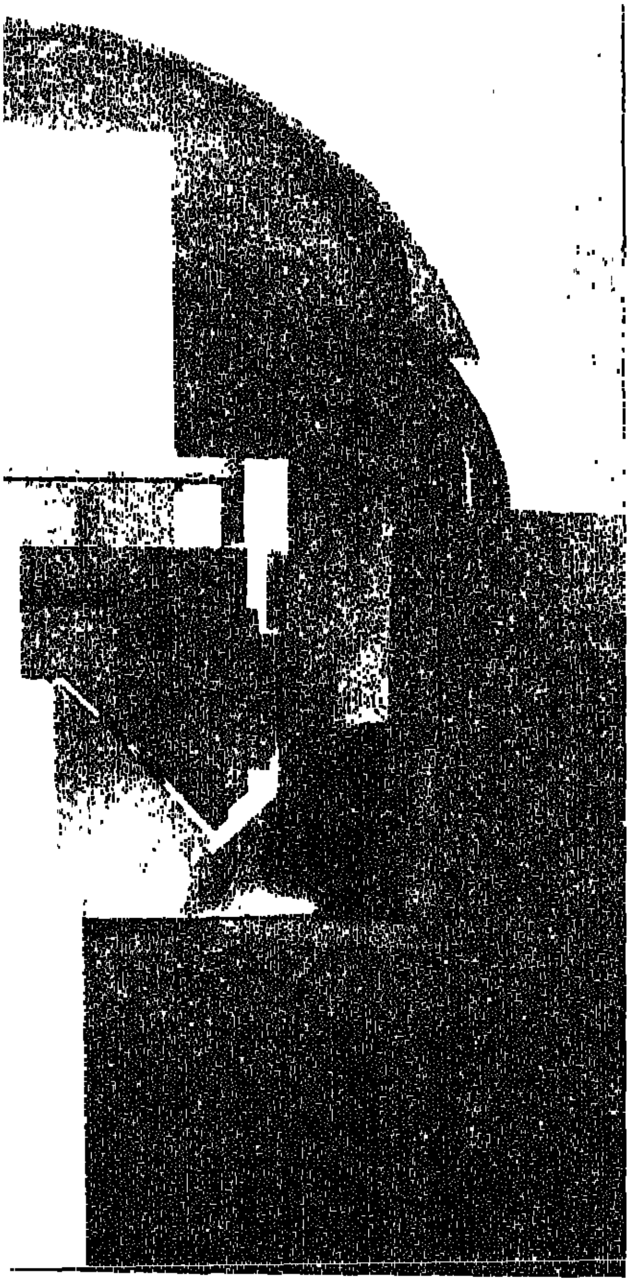
MINUTE DETAILS THAT MATTER: MEASURING ON MOLECULAR AND ATOMIC SCALES

The ability to manipulate clusters of molecules and atoms and even individual atoms has opened a new frontier in manufacturing. Already visible on the horizon are an impressive array of micromachines, quantum well lasers, nanotubes, and other so-called nanotechnologies with great commercial and industrial potential.

MEL researchers are actively exploring this domain of the nearly infinitesimal. Some are building atomic-scale measurement tools to support manufacture of nanometer-sized

Atomic topography of a *graphite crystal* is laid bare by a scanning tunneling microscope (STM). Deep inside M^3, an STM probe is mounted on a sliding carriage. Precise positioning is achieved with a combination *of laser* interferometry and piezoelectric control.

***Not your ordinary* measuring machine, M^3 will serve as an exploratory tool for manufacturing methods that form parts from structures as small as clusters of molecules. The initial metrology goal is to measure the distance *between two points* over an unprecedented range (50 mm by 50 mm) with 1-nm accuracy.**

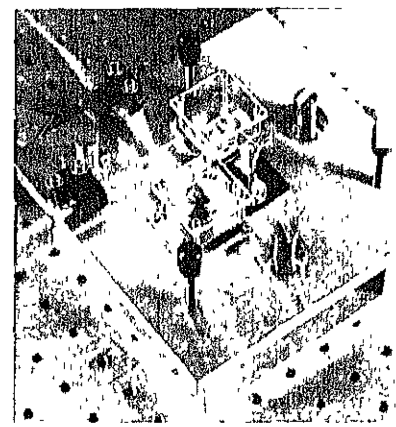


devices Others are using the growing array of scanning-probe microscopes and other tools to address current manufacturing issues A few examples follow

Molecular Measuring Machine (M^3): In the realm of nanotechnology, M^3 will be able to accomplish a feat akin to measuring the distance between two short needles in a haystack the size of the Earth. Pushing well beyond the current state of the art, M^3 will be capable of positioning and measuring to atomic-scale accuracies over an area of 25 square centimeters, a measurement capability essential for supporting efficient manufacture of the next generations of integrated circuits. Now undergoing development and testing, the machine will be used to characterize distances, geometries, and distortions of arrangements of atoms on surfaces. This unmatched capability will enable development of reference artifacts, such as calibrated grids for aligning photomasks on silicon wafers, and other measurement aids to meet the needs of semiconductor manufacturers and the emerging nanotechnology industries M^3 also will serve as a laboratory for building novel molecular electrical and mechanical structures

Even before it is fully operational, M^3 is paying dividends Researchers identified a method for significantly improving the accuracy of laser heterodyne interferometers, which was adopted by two U S. makers of the instruments It also has pointed the way to techniques for isolating broadband vibrations that can interfere with precision machining and nanofabrication operations.

Manufacturing Applications of Scanning-Probe Microscopy: The sca ning tunneling electron microscope, whic can trace part of its origins to pioneering work done at NIST during the 1960s, has given rise to a growing arsenal of instruments for studying atomic structure and properties. At MEL, researchers are addin to this arsenal with their own innovations, and they are applying their tools to a num



ber of technical problems One group is pioneering methods for profiling and meas uring surface textures, necessary for on-lin control of coating and finishing processes. As part of this effort, MEL scientists and en gineers evaluated a promising infrared sen sor and imaging technique for in-process inspection of plasma spray coatings

Another group is developing a calibrated atomic-force microscope, which will be used to support the semiconductor industry's efforts to develop lithographic, or print ing, methods for manufacturing integrated circuits with nanometer-sized devices With industrial collaborators, MEL researchers also are using scanning-probe microscopy to address material processing issues impeding commercial development of promising emerging technologies

MEL will use this extremely accurate, calibrated atomic-force microscope to support the needs of the semiconductor, optics, magnetic storage, and other industries that require high accuracy, high-resolution measurements of surface features with dimensions that are a small fraction of a micrometer.

MULTIFACETED RESEARCH ON CMMs

With more than 20,000 coordinate measurement machines operating in factories around the world, CMMs are indispensable tools for many manufacturers. They are used to verify process performance and to inspect the quality of finished parts and products

MEL is embarking on a major upgrade of facilities to strengthen and broaden its CMM-related technical activities The Laboratory's Moore M48 CMM is now housed in a room with exacting temperature control—to within 0 05 degree Celsius This facility will host expanded research on the effect of temperature changes on CMM accuracy as well as other aspects of measurement precision and reliability.

Using this research, MEL can further improve its software-based methods for enhancing the accuracy of CMMs by correcting for temperature influences and other factors that undermine measurement accuracy. But U.S. industry already is benefiting from this MEL-developed technology Several U.S CMM manufacturers have incorporated the technology into their products An executive at one of the companies credits the MEL innovation as being instrumental in his firm's success in developing an "ultra-precision measuring machine that is competing favorably in the international market" by meeting industrial customers' needs to "meet stringent quality and productivity goals."

The Laboratory also is obtaining a new gear-measuring CMM as it intensifies its focus on the technical needs of the U S. gear industry. Other activities range from characterizing the performance of CMM probes to developing a manufacturing measurement database to guide strategies for efficient inspection of parts with complex geometries. In addition, MEL researchers are conducting an assessment of industry needs for new dimensional inspection techniques. Specific examples include

Calibrations and Special Tests. Responding to industry requests, NIST is expanding its precision measurement services for CMM manufacturers and users. In collaboration with the Y-12 Plant at the Department of Energy's Oak Ridge Centers for Manufacturing Technologies, NIST will calibrate end standards and step gages up to 1 35 meters long to an accuracy of 0.7 micrometer per meter—equivalent to about one-hundredth of the diameter of a human hair The new measurement service, once available only from foreign laboratories, will be carried out at the Y-12 Plant in Oak Ridge, Tenn., by NIST. As the Y-12 facility's measurement equipment is characterized more fully, services may be expanded to two- and three-dimensional measurements

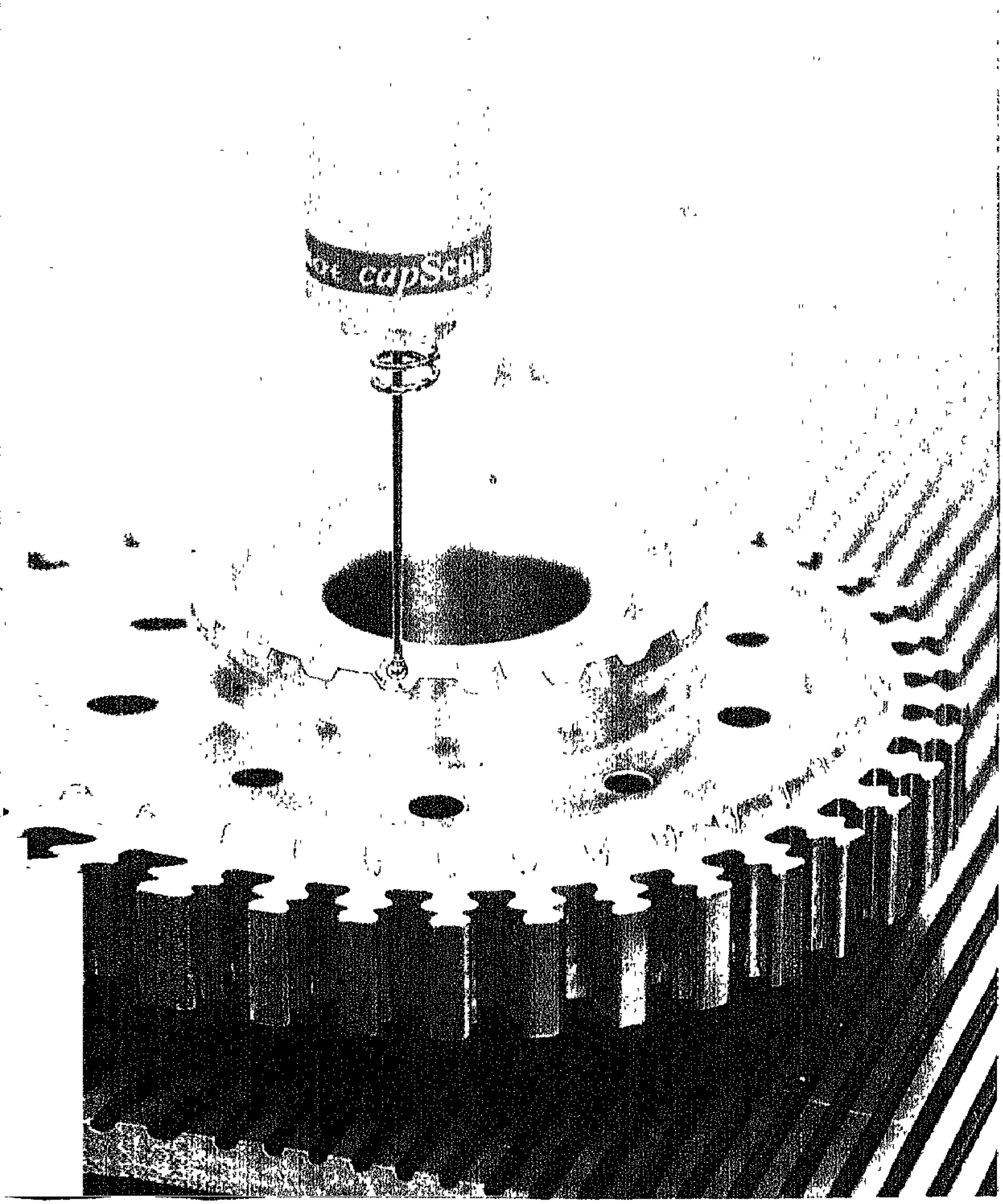
Interim Testing of CMM Performance. Typically, companies calibrate their CMMs about once a year, but without periodic checks between calibrations, they cannot be certain that their machines are continuing to measure accurately In collaboration with Caterpillar, Giddings & Lewis, and the U.S. Air Force, MEL has developed a simple testing device for regularly assessing CMM performance. With the MEL innovation, a complete system check-out can be accomplished in 15 minutes. Giddings & Lewis Measurement Systems of Dayton, Ohio, has announced that it is commercializing the interim testing standard.

Ensuring the Accuracy of CMM Data-Analysis Software. CMM measurements are derived from three-dimensional coordinates recorded at each point where the machine probe touches the part being inspected. From this sampling information, the machine extrapolates the geometric "fit" of the part. Obviously, the quality of the analysis greatly influences the accuracy of CMM measurements, which, in turn, directly impacts product quality.

In fact, firms have reported considerable variability among data-analysis software packages. In response, MEL devised a testing system for evaluating the performance of the CMM software against a reference set of geometric fitting algorithms. Already

How accurate? An MEL algorithm testing system (ATS) evaluates the performance of data analysis software embedded in coordinate measuring systems. Tested at more than 25 U.S. firms, the ATS is the basis for a pending standard for assessing software quality.

MEL innovation enables between-calibration checks of CMM performance. Adopted by a major CMM manufacturer, the kinematically mounted, calibrated ball bars are indexable throughout the CMM work zone.



Improving the manufacture and quality assurance of precision gears is the aim of expanded MEL programs and services addressing the measurement needs of the U.S. gear industry. A new inspection system will be devoted to gear-measurement issues, and MEL is a partner in the new national Center for Gear Metrology.

adopted by a number of users an
turers of CMMs and data analysi
the testing system is now being e
into a national standard Soon, M
establish a national algorithm tes
ice for coordinate measuring sys

INSPECTION SYSTEMS FO TOMORROW

MEL is participating in an indust
effort, sponsored by the National
Manufacturing Sciences (NCMS)
both to increase the speed of insp
tems by a factor of 10 to 100 and
detection of non-statistical surfac
More rapid inspection would spe
back for identifying and correctin
ing errors. By increasing the num
distribution of inspection points,
generation inspection system" als
produce more reliable measurem
complex parts. An MEL testbed,
developed in collaboration with c
members of the NCMS consortiu
focus on integrating analog touch
laser triangulation systems, and
vanced sensors as well as on usi
model data for programming insp
routines and evaluating results. A
equipped with an open architectu
ler based on NIST's Real-Time C
tem will serve as the research pla

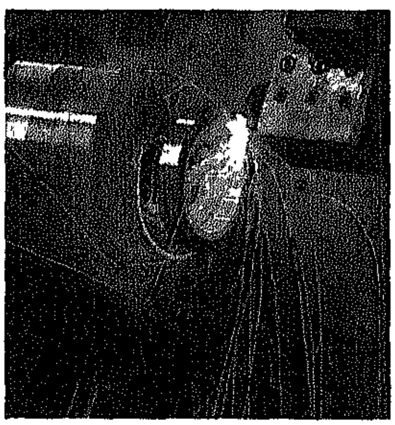
In a complementary project, MEL
ers are studying approaches to de
inspection systems with the rang
and the dexterity needed to meas
wise difficult-to-reach features, a
mobile bodies and other large as
products The system now under
ment features visual methods for
inspection routines, which can be
off-line simulations before they a

EMPHASIS ON PERFORMANCE AND CONTROL

BETTER SMARTER TOOLS

Advanced technology doesn't necessarily make the manufacturer, but it can make a difference in a company's competitive fortunes Consider the results of a recent study of five major manufacturing industries, including fabricated metal products, electronics, and transportation equipment At plants using modern technologies, average sales per employee exceeded by about one-third the average for all manufacturing plants in the industries studied

MEL research on machine tools and on combinations of tools and measuring machines has several goals One is to push beyond the performance envelope of current technology to achieve, for example, higher machining accuracy, better control, faster throughput, longer tool life, and greater process flexibility and versatility Work in this area directly benefits the U S machine tool industry, once the world leader but now surpassed by Japan, Germany, and Italy



Another MEL goal is to assist industry in developing efficient, economical processes for manufacturing with ceramics and other advanced materials that have vast potential for commercial and defense-related applications. A third goal is to develop cost-effective methods for enhancing the performance and capabilities of machinery already on the factory floor.

R&D efforts address a diverse array of technical topics Among them

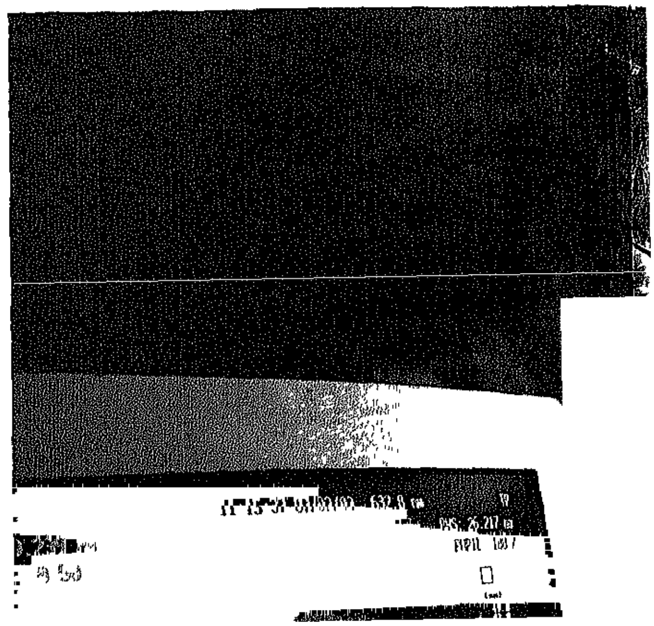
- characterization of machine-tool performance,
- real-time error correction,
- advanced machining methods for high-performance materials;
- ductile regime grinding,
- precision finishing;
- applications of robots in welding, grinding, construction, and large-scale assembly,
- sensors, sensor-information processing, and sensor integration;
- open-architecture control systems;
- integration of tools, work cells, and manufacturing systems,
- machine vision, mobility, and intelligence,
- applications of artificial intelligence and expert systems; and
- experimental machine tool designs.

A sampling of research projects illustrates some of the technological advances MEL is pursuing with the aim of helping U.S. industry to improve its manufacturing capabilities

ADVANCED MACHINING METHODS

Despite glowing forecasts of widespread commercial applications, ceramics and other advanced materials have yet to live up to their broad potential. Difficulties in machining the materials into finished parts pose major obstacles, resulting in high

Research on hard turning investigates fundamentals of tool wear and approaches to extending range of materials that can be machined. Findings point the way to improvements in tool design and material selection.

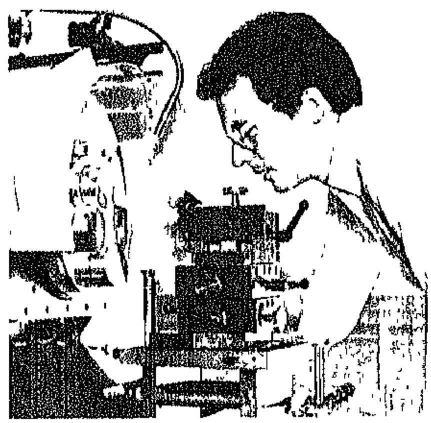


Components of advanced optical systems must be machined to near perfection. MEL is developing an optic test method for measuring the surface shape of ultraprecision optics. Contours of an aspherical mirror are profiled in the image, revealing how far it deviates from the ideal surface.

manufacturing costs that have largely restricted their use to very specialized applications

MEL researchers are working to eliminate these obstacles by developing and demonstrating new fabrication methods Their objective is to minimize manufacturing costs while improving machining precision and accuracy through process improvements, sensor integration, and intelligent controls Basic studies of selected materials and processes have identified and characterized some of the fundamental factors impeding improvements in machining precision and productivity

This information guides experiments to identify improvement strategies. For example, MEL scientists and engineers are now investigating use of alternative chemical dressings during grinding of ceramic materials The approach holds promise for accelerating material removal without degrading



the strength of finished parts. In fact, study results indicate that ductile regime grinding can significantly increase the strength of machined ceramics.

Diamond turning produces off-axis parabolic mirrors for an infrared optical measurement system. An MEL-developed theory accounts for chemical factors that influence the wear of diamond-cutting tools.

In other recent work, MEL researcher
developed a rapid, post-process met
polishing diamond-turned componen
advanced optical systems The econ
method improves the quality of surfa
finishes, without affecting componen
geometry

Other advanced machining projects a
developing methods to:

- Improve the precision of hard tur
For some manufacturing applicat
such as cutting dies from hard,
high-carbon steels, greater precis
can replace the grinding step and
consequently, enable cost-effecti
small-batch production.
- Reduce surface damage caused b
grinding of ceramics
- Extend the life and performance r
cutting tools.
- Improve on-line monitoring and c
of machining processes.

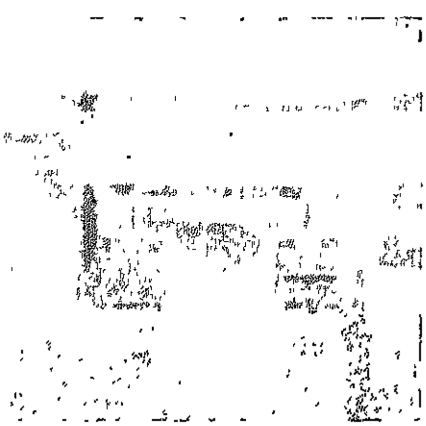
ENHANCING THE ACCURACY O MACHINE TOOLS

Since the 1970s, MEL has been refin
extending the applications of an espe
productive approach to improving ma
tool performance Called "determinis
metrology," this strategy has pointed
way to software-based methods for e
ing accuracy Elements of the strateg
adopted first by CMM manufacturers
a growing number of machine-tool m
are applying components of the techn

Machine tool accuracy is influenced
number of factors. They include the c
of machine components and their ass
machine geometry, temperature chan
and dynamic forces affecting the mac
operation. Each factor can contribute
inaccuracies, or errors, many of whic

predictable The MEL approach is to characterize and model these systematically repeating errors, and then develop error-compensating software Instructions for correcting inaccuracies are either programmed into the controller or other electronic hardware.

Capitalizing on the increasing power of computers, MEL researchers continue to improve upon the technology The newest generation of the real-time error corrector



Thermal mapping helps MEL researchers to characterize temperature-related influences that affect the cutting accuracy of machine tools.

features three levels of control for detecting and automatically compensating for machining inaccuracies. Additional improvements are now under development, but some of the processing-improving benefits of the technology already are being realized

Incorporated into a flexible manufacturing workstation at the Portsmouth Naval Shipyard in New Hampshire, in-process inspection and error correction contributed to significant improvements in shipyard production of "submarine-safe" fasteners. With the workstation, developed by NIST in collaboration with the shipyard and two industrial partners, productivity has increased by more than 300 percent, manufacturing costs have dropped significantly, and the rejection rate has fallen to less than 1 percent.

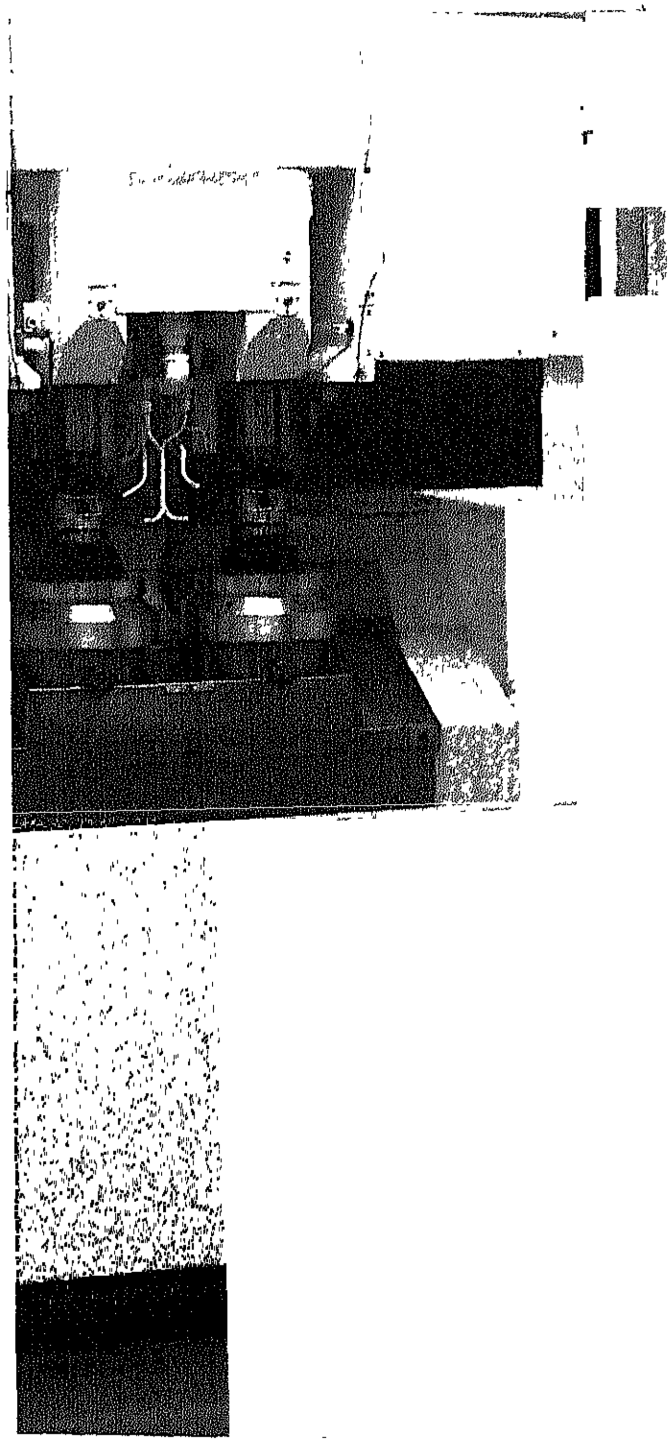
Giddings & Lewis, the nation's largest machine-tool manufacturer, is incorporating MEL-developed real-time control algorithms into its high-precision piston-turning machines. And Saginaw Machine Systems is adapting methods for correcting inaccuracies caused by thermal changes and geometric irregularities, offering the technology as an add-on capability to its current line of turning centers

'OPENING UP' MACHINE TOOL CONTROLLERS

Machine-tool controllers are proprietary products—"black boxes" that necessitate costly, customized solutions to manufacturers' needs to enhance capabilities and integrate equipment MEL's response to this predicament is to develop an open-architecture controller that will easily accommodate software and hardware enhancements supplied by third-party vendors.

Built on a personal-computer platform—a standard in itself—MEL's open-architecture controller will be based on public domain software developed by NIST and collaborating organizations.

By "opening up" the controller, MEL and its partners intend to spur innovations in manufacturing in much the same way that publishing the architecture of the PC triggered a wave of independently developed software applications for personal computers. The anticipated benefits of an open-architecture controller are numerous. For one, the availability of modular, easily integrated software and hardware from a variety of sources would extend the life and enhance the performance capabilities of controllers. Controller upgrades could be accomplished without



This high-precision piston turning machine was the focus of a collaboration involving MEL, NCMS, Giddings & Lewis, Ford, and GM. Elements of MEL's accuracy-enhancing technology will be incorporated into the machine.

the complex and costly re-engineering now required to add sensors and make other enhancements to proprietary controllers

Early experimental versions of MEL's open-architecture controller have been demonstrated at the Laboratory's Automated Manufacturing Research Facility. Refinements and further developments are being pursued with machine tool builders and users as well as suppliers of controller

components Plans call for testing controller prototypes at manufacturing plants.

IMPROVING MACHINE I.Q.

For all their sophistication, even today's most advanced machines have not evolved much beyond technology's equivalent of the dinosaur age: They're still long on brawn and short on brains Yet, intelligent machines—those with some capacity to acquire and apply knowledge—are fundamental to controlling processes, improving worker and corporate decisionmaking, reducing costs, improving quality, and building the capability to respond rapidly to changing customer requirements and emerging market opportunities. For example, intelligent, highly automated processes can make it economical to produce small lots of customized products And, because of the flexibility enabled by intelligent control, a single line can manufacture a variety of products, while retooling is kept to a minimum, saving time and money

MEL research on intelligent machines and systems, which is coordinated with complementary work on computer-integrated manufacturing, spans:

- sensors, real-time processing of sensor-gathered information, and sensor integration;
- simulation;
- advanced robotics, including machine vision and mobility,
- machine learning;
- experimental manufacturing applications of neural network technology, and
- reference architectures, or frameworks, for real-time control systems.

The NIST Real-Time Control System (RCS), developed by MEL robotics researchers, integrates and orchestrates the activities of all components and subsystems that must cooperate electronically in order to manufacture "intelligently." The hierarchical control system is adaptable, accommodating new technologies and future changes without jeopardizing overall performance Now in its fourth generation, the RCS is able to process signals from many vision, touch, force, and tension sensors into a unified world model. Artificial intelligence planning and control algorithms then can be used to generate complex behaviors requiring force controlled manipulation, hand/eye coordination, obstacle avoidance, and active foveal/ peripheral vision.

First demonstrated at the Laboratory's Automated Manufacturing Research Facility, the NIST RCS has been used in a variety of applications These include the Westinghouse Corp 's automated motor assembly testbed, a control system for a U S Postal Service general mail facility, commercial-floor-cleaning and hospital-service robots being developed by the Transitions Research Corp , and an intelligent workstation for deburring and chamfering components of jet engines, which MEL is jointly developing with the United Technologies Research Center for the U S. Navy.

The RCS is being used in the RoboCrane Large-Scale Manufacturing Testbed. Work here is addressing teleoperation and autonomous control issues influencing performance of a wide variety of tasks that require lifting and positioning large and heavy loads The RoboCrane can manipulate tools for grinding, cutting, welding, painting, paint stripping, inspecting, and slip-form or spray casting. It also can manipulate and precisely position heavy objects such as steel beams, plates, fixtures, motors, pumps, and assemblies Applications include manufacturing and assembly of large aircraft, trucks, ships, and heavy machinery, as well as construction of bridges, buildings, and other infrastructural systems.

Experimental "intelligent" vehicles are another proving ground for the NIST RCS. MEL engineers are investigating vision-based approaches to automating driving tasks, using a U.S. Army "humvee" as a testbed. Gathering and processing input from cameras and an array of sensors mounted on the robotic vehicle, the RCS directs and coordinates the activities of mechanical subsystems, enabling the driverless humvee to follow lane markings and maintain safe following distances.

Leave the driving to the computer. A robotic military "humvee" serves as a testbed for integration and intelligent-control technology. The MEL project addresses both defense and commercial needs for "intelligent" vehicles.

ASTER, NIMBLER MORE PRODUCTIVE FACTORIES

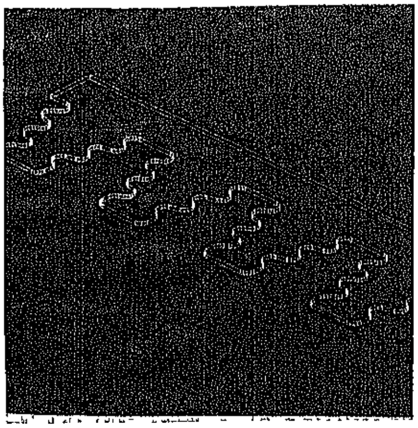
nformation is becoming the currency of success in manufacturing. To cash in, however, a firm not only must have comprehensive collections of data on /thing from designs and processes to lier performance and customer require-s, but it also must have the tools to ss the right information, at the right and in the right form.

ner words, the firm must be a fully uter-integrated organization. And, ; in fact, very few firms merit that iption. Incompatibilities among the reds of different types of computer-systems for design, engineering, and facturing undermine exchanges of nation within and between companies. large manufacturing companies built their own versions of the United ns, investing substantial sums and ndous effort in building software trans-that mediate data transfer between etary systems. This is an unsatisfac-olution and, bad as it is, it's not afford-or most small and medium-sized anies.

iate today's information logjams and acturing firms can move beyond the uterization of discrete tasks and pursue unities to improve almost every facet nufacturing and business performance. y new forms of manufacturing and busi-rganization become possible.

esearch is opening the way to ad-d manufacturing applications of ation technology by helping to build l components of the supporting infra-ure. With industry, it is developing rds for networking, electronic data nange, and digital product data shar-major goal is to enable computer-ated manufacturing through the use of led "plug compatible" software.

The information revolution in manufacturing is spreading beyond the mechanical parts world to other industries with similar needs. This allows the information technology community to collaborate with the apparel community to bring the capability of product data exchange through STEP to apparel production.



Now in its second decade, MEL research on computer-integrated manufacturing is yielding useful results for industry. At the Automated Manufacturing Research Facility, researchers pioneered methods for distributed control of manufacturing databases and developed functional architectural models and interfaces for integrating processes and information. Several companies, including Boeing and General Electric, have credited MEL-developed approaches to coupling information, tools, and overall manufacturing system control with helping to guide their factory networking and integration efforts.

The Laboratory and all of NIST are intensifying efforts to build the underlying, core technologies of the supporting information infrastructure necessary for world-class manufacturing performance in the 21st century. NIST and its laboratories are key participants in two major federal programs—the National Information Infrastructure and the High Performance Computing and Communications program—that aim to help U.S. companies progress to the leading edge of manufacturing's next revolution. (See box on page 17.)

MOVING IN STEP WITH INDUSTRY

NIST and MEL have played an instrumental role in an industry-led effort to create an internationally accepted system for electronic exchanges of manufacturing product data. With pending official approval of the first version of the Standard for the Exchange of Product Model Data (STEP) by the International Organization for Standardization (ISO), manufacturing has begun to progress beyond the paper-burdened age of the blueprint. STEP creates an unambiguous, computer-readable format for presenting all useful information about a product throughout its life cycle—from its inception in design through maintenance and service.

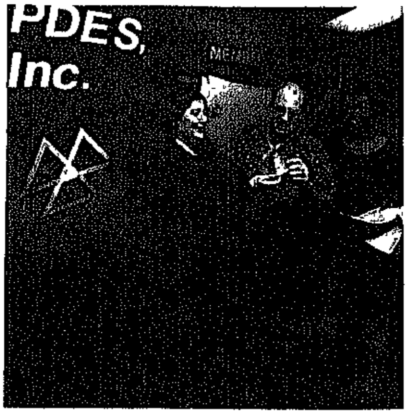
With STEP, accurate, up-to-date product information will be immediately available to all units in a company and to suppliers and customers—a prerequisite for truly concurrent engineering and computer-integrated manufacturing.

In fostering the evolution of STEP, MEL:

- Chairs the ISO committee that is coordinating development of the evolving standard
- Chairs the 550-member IGES/PDES Organization, the national body that communicates U.S. requirements to ISO.
- Contributes to the standard's technical development in collaborative work performed with industry, as led by the IGES/PDES Organization and PDES Inc., a consortium involving more than 20 major U.S companies.
- Hosts and staffs, with partners from industry, universities, and federal agencies, the National Initiative for Product Data Exchange (NIPDE) Sponsored by the Departments of Commerce, Defense, and Energy as well as the National Aeronautics and Space Administration, NIPDE is credited with accelerating the standard's development by coordinating private- and public-sector efforts
- Operates a national testbed to investigate design and manufacturing applications enabled by the standard.

Although mechanical-parts manufacturing was emphasized during STEP's early development, the Laboratory and NIPDE are working with other NIST laboratories and private-sector organizations to extend the standard and deliver its anticipated benefits to more manufacturing industries: apparel, electronics, chemical processing, and construction

With the United Technologies Research Center and the U.S. Navy, MEL is developing an advanced robotic work cell to make high-precision chamfers, or beveled edges, on turbine engine components. Robot chamfering trajectories are generated off-line from computer-aided design data (left), greatly reducing programming time. The work cell also incorporates MEL sensor-integration technology. Force feedback keeps the cutting bit of the robot's intelligent chamfering tool (right) on the part's edge.



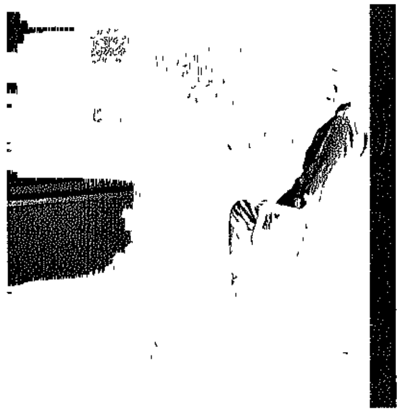
PARTNERSHIPS FOR MANUFACTURING PROGRESS

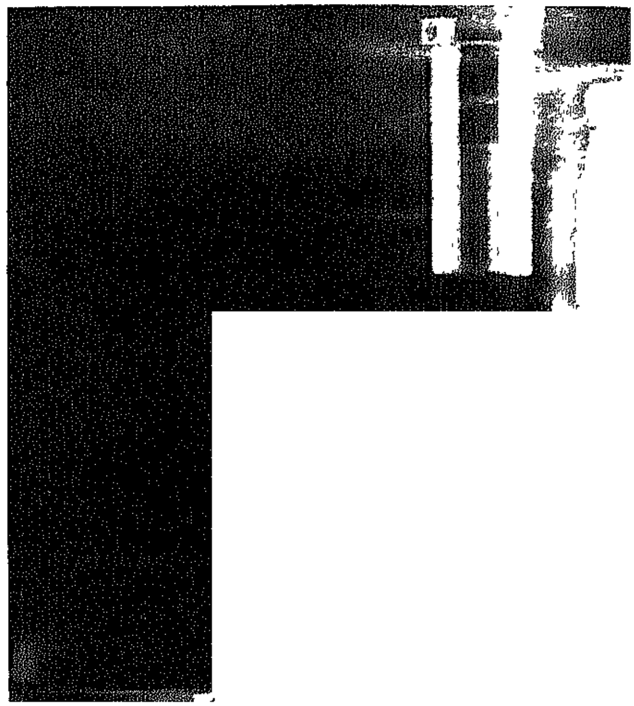
Taking full advantage of the opportunities presented by information technology requires sustained cooperative efforts. That's because the technology, by its very nature, is collaborative The principal competitive advantages it offers will be realized through new flexible forms of production and organization built on easily reconfigured linkages—as between original equipment manufacturers and their suppliers and customers

As much as individual companies, entire industries will benefit greatly from an infrastructure that enables information-driven manufacturing and commerce. As illustrated by the following examples, MEL is forging technical partnerships with industry to ensure that these benefits are realized sooner rather than later.

Rapid Response Manufacturing. With funding from NIST's Advanced Technology Program, five major U.S. manufacturers have joined with a group of software companies and MEL to develop computer-based tools and methods to reduce product-development time and, in the process, increase product quality and reliability The participating companies are members of a consortium administered by the National Center for Manufacturing Sciences For its part, MEL has assessed the state of the art in rapid prototyping and other key technology areas Using STEP, consortium members are developing an integrated part and process model MEL researchers are concentrating on building a complementary model for databases on machine tools and other manufacturing resources This model will help build a needed link between part design and manufacturing capabilities, essential to process planning and estimating manufacturing costs.

Factory Networking. The "information content" of manufacturing is growing almost exponentially and, with it, the importance of trouble-free communication over factory networks. Network problems can shut down production lines. With the General Motors Corp., MEL is developing diagnostic software for troubleshooting communications problems in factory networks One outcome is a prototype of a tool to assist factory personnel in monitoring and troubleshooting computer-integrated manufacturing systems. Based on national and international standards, the tool was developed in GM and MEL laboratories containing computing equipment and communications systems representative of a modern factory.





Product data exchange standards enable parts to be made using digital technology. With industrial organizations, such as the PDES Inc. consortium and the IGES/PDES Organization, MEL has played a key role in the development of STEP.

Robot goes with the flow—the flow of computer-processed images that is. A new MEL testbed will be devoted to vision-based approaches for improving robot mobility in unstructured environments, such as factories, construction sites, and hospitals.

Electromechanical transducer directs ultrasonic pulses toward reference "blocks" calibrated by MEL for aerospace manufacturers and others that use the blocks to set their ultrasonic inspection systems. MEL work on sensors ranges from development, processing, and integration of sensors to measurement services.

INFORMATION-DRIVEN MANUFACTURING

Under the federal government's High Performance Computing and Communications program, NIST is embarking on a major initiative to speed development of advanced manufacturing applications of computer-integrated, electronically networked technologies Based in MEL, the multiyear initiative, called Systems Integration for Manufacturing Applications (SIMA), involves all eight NIST laboratories, with strong participation by U.S. industry, universities, and federal agencies

Launched in 1994 with a budget of $9 million, which is slated to grow to more than $25 million, SIMA has four major components

Manufacturing systems R&D will investigate and evaluate manufacturing uses of high-bandwidth communications links and other high-performance information technologies. Specific aims are to develop:

- new, integrated tools and methods for collaborative design;
- modular approaches to reconfiguring manufacturing processes,
- electronic information-sharing methods that are most effective for specific applications;
- communication protocols to achieve seamless networking;
- application protocols for design, process planning, and other information uses;
- specifications for enterprise-wide databases for product model data; and
- a production control environment

Technology transfer mechanisms, such as electronic information services developed with industrial collaborators, distributed collaborative work environments, and technology demonstrations, are integral to the program

Standards development is an explicit SIMA objective. Work will focus on developing high-quality standards necessary to enable data exchange among all computer-aided activities directly and indirectly related to manufacturing. Part of this effort will be devoted to devising performance measures and conformance tests for commercial implementations of standards

The Advanced Manufacturing Systems and Networking Testbed will serve as a laboratory and proving ground for researchers participating in SIMA projects. A "virtual" testbed, the facility will feature an emulated production control environment built with existing commercial systems, and it will provide high-performance computing and networking capabilities for collaborators inside and outside of NIST

At the end of the 5-year program, MEL and its partners will demonstrate a fully integrated set of applications, such as linking design and manufacturing activities at remotely located sites.

TECHNICAL ASSISTANCE TESTBEDS SERVICES

A provider of fundamental measurement services, a neutral facilitator that helps the private and public sectors set technical priorities, and a high-quality performer of R&D, MEL is a basic resource for U.S manufacturers There are many ways for companies to tap this resource. Opportunities for collaboration include joint research at the Laboratory's 14 testbeds, Cooperative Research and Development Agreements, participation in "round robins" that assess the current state of industry's measurement practices, and other formal and informal mechanisms. In addition, the Laboratory offers a growing array of measurement services that are used each year by hundreds of U.S firms.

NATIONAL MACHINE TOOL PARTNERSHIP

A toll-free call puts U S. machine tool builders in contact with manufacturing engineers and scientists at NIST and Department of Energy laboratories. During the first year of the National Machine Tool Partnership, more than 1,000 companies tapped this direct link to federal technical expertise and capabilities Major areas of focus include: machining, grinding, measurements, design, programming, and materials. Call: 1-800-358-6651.

TESTBEDS

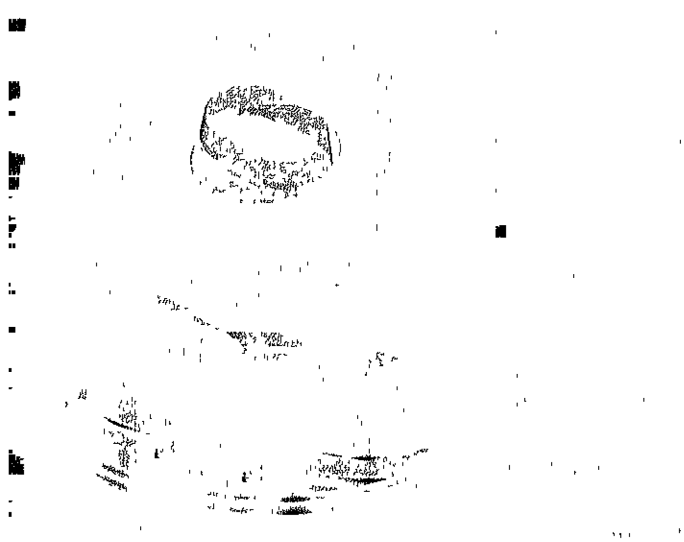
MEL testbeds leverage public and private research efforts and resources and are effective vehicles for communicating and demonstrating technical advances At these facilities, Laboratory staff members work side-by-side with developers of new manufacturing technology products, prospective users of those products, and collaborators from universities and other organizations with complementary technical objectives

MEL'S MACHINE SHOP PROVIDES A 'REALITY CHECK'

MEL has its own machine shop, which designs and fabricates one-of-a-kind instruments and experimental apparatus to meet the special equipment needs of NIST researchers. Staffed by skilled instrument makers and machinists, the 50-person operation has a workload comparable to that of small machine shops that supply parts to customers in high-technology manufacturing industries.

The MEL shop has served as a proving ground for manufacturing modernization strategies, such as retrofitting manually operated machine tools with computer controls and automating cost-estimation and process-planning procedures. These modernization activities have improved and expanded the shop's capabilities They also have guided MEL's outreach efforts to acquaint the managers of small machine shops with the benefits of automating their operations

While MEL's "factory" will continue to serve as a technical resource for small metalworking operations, the machine shop also will become a local node in the National Advanced Manufacturing Testbed that the laboratory is developing. (See page 3.) As part of the NAMT, the machine shop will serve as an initial test site for demonstrating and refining experimental manufacturing technologies and networking applications.



Support base for a helium vessel to be used at the NIST research reactor. Graphic shows how the part was cut. MEL's machine shop fabricates special equipment for NIST researchers and provides technical help to small metal-working operations.

The scope of R&D efforts at MEL testbeds ranges from a broad set of interrelated technical activities, as in the case of the Automated Manufacturing Research Facility, to projects concentrating on specific manufacturing applications and technologies

Automation and Integration

Automated Manufacturing Research Facility
Contact: Richard H.F. Jackson, Acting
(301) 975-3401
email: jackson@micf.nist gov

National Advanced Manufacturing Testbed (under development)
Contact Richard H.F. Jackson, Acting
(301) 975-3401
email. jackson@micf.nist.gov

Manufacturing Applications of Information Technology

Advanced Manufacturing Systems and Networking Testbed
Contact Mark E. Luce
(301) 975-2802
email luce@cme.nist.gov

National Testbed for Product Data Exchange
Contact Jeane Ford
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email. ford@cme nist.gov

Product Data Exchange Standards for the Apparel Industry
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(301) 975-3747
email: ford@cme nist.gov

Rapid Response Manufacturing
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email: jurrens@cme.nist.gov

Computer-Aided Manufacturing Systems Engineering Laboratory
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email: mclean@cme.nist.gov

Process Planning Testbed
Contact: Steven Ray
(301) 975-3524
email. ray@cme.nist.gov

Machine Tools, Inspection Systems, and Intelligent Machines

Enhanced Machine Tool Controller
Contact: James S. Albus
(301) 975-3418
email. albus@cme.nist gov

Next Generation Inspection System
Contact. Martin Herman
(301) 975-3441
email: herman@cme.nist.gov

Advanced Machine Tool Structures Testbed
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Fred Rudder
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email frudr@enh.nist.gov

Mobility Testbed
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(301) 975-3441
email: herman@cme.nist.gov

High-Stiffness Machining Testbed
Contact: Chris Evans
(301) 975-3484

RoboCrane Large-Scale Manufacturing Testbed
Contacts: Roger Bostelman
(301) 975-3426
email: bostel@cme.nist.gov or
Ken Goodwin
(301) 975-3421
email: kgoodwin@enh.nist.gov

Others

National Center for Gear Metrology (at the Oak Ridge Centers for Manufacturing Technologies, Oak Ridge, Tenn)
Contact Dave Stieren
(301) 975-3197
email dstieren@enh nist gov

MEASUREMENT SERVICES

MEL offers a variety of measurement services that support manufacturers' quality assurance and process control efforts Calibrations and special tests characterize instruments, devices, and reference artifacts, providing traceability to national and international standards

Calibrations

Length Measurements:
- Gage Blocks
- Line Standards
- Surveying Tapes
- Surveying Leveling Rods
- Sieves
- Step Gages

Diameter Measurements
- Plug Gages—External Diameter
- Measuring Wires for Threads and Gears
- Spherical Diameter Standards—Balls
- Internal Diameter Standards—Ring Gages
- Special Tests of Length and Diameter

Microelectronic Linewidth Standards

SEM Magnification Standards

Particle Size Standards

Complex Dimensional Standards:
- API Threaded Plug and Ring Gages
- Threaded Plug and Ring Gages
- Special Tests

Optical Reference Planes and Roundness Standards.
- Optical Reference Planes (flats)
- Roundness Calibration Specimens

Angular Measurements
- Angle Gage Blocks
- Optical Polygons
- Rotary and Indexing Tables
- Wedges

Laser Frequency/Wavelength

Surface Texture
- Roughness Calibration Specimens
- Step Height Measurements

Mass Standards
- Weights Ranging from 1 mg to 30,000 kg
- Weights for Deadweight Pressure Testers
- Measurement Assurance Program for Mass

Force Measurements:
- Force Transducers to Over 4 4 MN (1,000,000 lbf)
- Special Tests of Force Transducers

Vibration Measurements
- Vibrations (Pickup Sensitivity, Frequency Range: 2 to 10,000 Hz)
- Special Shock Measurement Services
- Special Tests of Pickup Sensitivity

Acoustic Measurements
- Microphone Pressure Response
- Earphones
- Special Tests of Acoustic Devices

Ultrasonic Reference Block Measurements:
- Aluminum, Titanium, or Steel Reference Blocks
- Velocity Reference Blocks

Ultrasonic Transducer Measurements:
- Transducer Power Output
- System Power Output
- Special Tests

Acoustic Emission Transducer Measurements (Amplitude and Phase Sensitivity versus Frequency)

Coordinate Measuring System Algorithm Testing and Evaluation

For information on NIST calibration services, call (301) 975-2002, fax (301) 926-2884, or email dittmann@micf nist gov

Standard Reference Materials

With NIST's Standard Reference Materials (SRMs), companies can verify the accuracy of measurement systems used in the laboratory and in the factory NIST offers more than 1,200 SRMs, a diverse collection of solids, liquids, and gases certified for chemical composition or physical properties Examples of categories of SRMs of interest to manufacturers are listed below:

Particle Size Standards
Surface Finish
Coordinate Measuring Machine Performance
Non-destructive Evaluation
Linewidth Measurement Standards
Scanning Electron Microscope Standards
Ultrasonic Power Standards
Acoustic Emission Standards

For information on ordering Standard Reference Materials, call (301) 975-6776, fax (301) 948-3730

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